Design of a Solid Rocket Motor for an Air to Air Missile

by

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ABSTRACT

This paper provides a conceptual design for a solid rocket motor for an air to air missile to meet a specified mission. The design will utilize a trade study process to develop the final design. First, a preliminary design of the solid rocket motor will be created as a baseline for comparison utilizing an analytical approach. Trade Studies will then be conducted on specific input parameters of the motor. The final stage will utilize the preliminary design and the results of the trade studies to create and refine a final design. The project will consist of analysis utilizing propulsion principles and BurnSim software as applicable, and will result in a comparison table comparing the final design against the preliminary design.
1. Introduction

Design for missile solid rocket motors is critical for modern warfare. Missiles are used amongst militaries all over the world, and provide the capability to precisely strike specified targets. Missions for different missiles are dependent on the specified type and required capability. Different applications of missiles include ballistic missiles, anti-ship missiles, and air to air missiles.

![Air to Air Missile](image1)

**Figure 1: Air to Air Missile**

A key example of an air to air missile is the AMRAAM AM-120. This medium range missile was developed as a result of a Joint Service Operational Requirement in the post-1985 timeframe. It is powered by a solid rocket motor and can achieve a speed of Mach 4 in a range in excess of 30 miles. In long range engagements, the AMRAAM utilizes inertial guidance and receives updated target information from the launch aircraft. Aircraft utilizing this weapon system today include the F-15, and F-16, and F-18 fighters. *(Reference Global Security)*

![AM-120A Missile](image2)

**Figure 2: AM-120A Missile (Reference AIM-120)**
Key to understanding a solid rocket motor’s design is to first understand the system it is powering. Although the composition of a missile includes numerous components, the four essential components include: a drive system, design, guidance systems, and warhead. The drive system is defined as the propulsion system utilized to power the missile to its specified target. The design is derived from the mission specifications and is the primary driver of the configuration and size. The guidance system calculates the missile’s current position and the position of the target, and then calculates a course between them. The warhead is the provider of primary destructive power to the target.

With the understanding of mission requirements and the configuration of the missile, the design of a motor can be investigated to validate compliance to a specific mission. Design of solid rocket motors has been addressed for numerous aspects in papers by researchers such as Richard Nakka and R. Clay Hainline, as well as addressed by government agencies including NASA.

This study will focus on the design of a solid rocket motor for an air to air missile under ideal conditions. The solid rocket motor will be designed to have a total mass no greater than 150 kg. The warhead mass provided is 25 kg and the guidance system allocation is 45 kg. The overall length cannot exceed 4 meters and the missile must also be able to operate at an altitude of 3,000 m and fly at Mach 4 for 60 km.

The design approach will include:

1) A Preliminary Design
2) Trade Studies
3) Final Design

A comparison of the preliminary and final design will be shown.
2. Theory

Fundamentals of Rocket Design

Rockets are the oldest type of aerospace propulsion system, dating back 2000 years to the Han Dynasty. Rockets are propulsion systems that produce thrust by accelerating mass through a nozzle. Chemical reactions are relied on by many rockets as an energy source. The propellant utilized in rockets consists of fuel and oxidizer components. The oxidizer is necessary since rockets are non air-breathing engines. Chemical rockets are categorized as: Liquid Propellant Rockets, Solid Propellant Rockets, or hybrid propellant rockets. (Text book reference)

Solid Rocket Motor

The solid rocket motor contains the propellant to be burned within a casing. The propellant takes the solid form called a grain, and once ignited, burns on the surfaces that are not inhibited by the case.

Figure xx: Solid Rocket Schematic

The grain cross section is a factor in impacting the thrust versus time and performance of the rocket. For example, as seen from figure xx, a propellant with a tubular grain design will have a thrust that will increase over time, while a rod and tube design will have a thrust that is relatively stable over time. The selection of grain design is dependent on application.
In addition, there are two types of burning for a solid rocket motor. The first, end burning charges, are designed so that burning begins at one end of the chamber until reaching the other end. The second, and more prominently utilized, is radial burning, where the propellant cross sectional area is changed over time. Radial burning provides high values of thrust for shorter durations of burn time. Figure xx shows the surface recession of a solid propellant.

**Propellants:**
Solid Rocket Motor Propellants are categorized as homogeneous, heterogeneous, or composite modified double base. The selection of the propellant, as well as looking at different input parameters of the motor, is fundamental to the design of the rocket motor.
A key parameter for understanding the impact of a propellant is the burning rate. The law that correlates the burning rate of a propellant to the critical pressure and propellant characteristics is Vielle’s Law:

\[ r_b = \frac{k(10^{-5} P_c)^n}{1000} \]

Where \( k \) represents the burning rate constant and \( n \) represents the burning rate exponent for a given propellant.

**Thrust Calculations**

To determine the thrust, three parameters are determined dependant on the design of the rocket and selection of propellant. These parameters are the thrust coefficient \( C_f \), the chamber pressure \( P_c \), and the throat area \( A^* \). Utilizing these parameters, the thrust of the rocket can be found utilizing the following expression:

\[ F_N = C_{f, \text{Actual}} P_c A^* \]

The thrust over time is dependent on the change in chamber pressure. The chamber pressure will be discussed below and varies with the burn area over time.

**Chamber Pressure**

The chamber pressure is calculated utilizing input parameters of the rocket as shown below:

\[ P_c = \left[ \frac{\rho_p A_p k(10^{-5}) \sqrt{RT_c}}{1000 A^* X^*} \right]^{\frac{1}{1-n}} \]

Chamber pressure plays a critical role in determining the hoop stress experienced by the casing of the solid propellant. This equation drives the decision of an appropriate material to be utilized.

\[ \sigma = \frac{P_c t_c (\text{Factor of Safety})}{d_M} \]
**Range Equation**

A fundamental element to meeting missile specifications is understanding the range and velocity of a rocket. For this project, the following expressions will be utilized to calculate these parameters at different time steps along the rocket trajectory.

Velocity Equation at each time step:

\[ V_{t+dt} = V_t + \frac{F}{m_t} \Delta t \]

Range Equation for each time step:

\[ x_{t+dt} = x_t + V_{t+dt} \Delta t \]

**Design Approach**

To assess the mission objectives for the air to air missile mission, a trade study approach has been developed.

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**Figure xx:** Trade Study Approach for Motor Design
1) Preliminary Design

   a) Analytical Approach

To begin the effort, an analytical preliminary design will be prepared. The overall goal of this preliminary design is to develop an ideal rocket motor to serve as a baseline for later trades.

The necessary input parameters necessary for the solid motor include propellant, motor diameter, various lengths (charge length, nozzle length), various thicknesses (motor casing and insulation), nozzle diameter, and material. In addition, configuration decisions will need to be made, such as the need for fins for the missile.

Utilizing these inputs, equations in accordance with solid rocket propulsion will be used to size the motor rocket. This approach will include analytical calculations based upon the provided inputs to size the motor. Included in the dependant variables are nozzle exit area, throat area, chamber pressure, burn rate, specific impulse, burn time, total mass, thrust, and range.

The final product will be a table documenting the results and assumptions for the preliminary design.

   b) BurnSim Comparison

The results of the Preliminary Design through the analytical approach will be compared to the simulation results from the BurnSim Software

2) Trade Studies

Once all parameters have been calculated and a design has been prepared, the second phase will be to compare input variables of the motor design versus mission output requirements. The following trades will be performed for this project:

   a) Material Trade: Utilization of different materials for the motor casing.

   b) Propellant Trade: The impact of selecting a different propellant with different parameters as the baseline will be traded.
c) **Variation of Dimensions Trade:** A trade study will be performed to understand the impact of changing the charge length and by changing the motor thickness of the rocket.

d) **Additional Trades:** With rocket motors, there are many variables that can be impacted. This task will allow for any additional trades (time permitting) to be performed to complete the final design.

3) **Final Design**

Utilizing the preliminary design and the trade study results, a design of the motor will be performed to meet the mission requirements. A similar analytical approach to perform iterations of the motor design utilizing the lessons learned from the trade study will be used. In addition, the BurnSim Software will be used at this stage to validate the final design based upon the preliminary design and trades. The result of the final design will include a comparison chart of the parameters utilized in the preliminary design versus the final design, and comparison plots from BurnSim.

In addition to the analysis, a visual computer aided design model will be created for the final design.

**Validation of Tools**

Prior to performing analysis on the specified mission requirements, a theoretical example from reference xx was utilized to validate both the analytical and BurnSim Software versus the expected thrust versus time curve. The analysis was performed for a radial burning solid rocket motor utilizing a tubular grain cross section. Figure xx shows the theoretical thrust profile for this cross section.

For the analytical approach, Microsoft Excel was utilized. Since mass flow rate and conduit area are dependent on time, time steps of 0.5 seconds were taken. Utilizing this approach, the burn time of the propellant was approximately 2.7 seconds and the resulting plot is shown below.
The BurnSim software, utilizing the same inputs, resulted in the following plot below. The blue line represents the thrust and the units for force are pound force and the burn time was calculated to be 2.59 seconds.

Figure xx: Thrust vs. Time for BurnSim

Figure xx compares the results of both the analytical approach versus BurnSim. The results outputted below show a percent error of 21% at time equals 0.01 seconds and a percent error of 10% at time equal to 2.5 s. The rationale behind this percent difference is the conversion between metric and English units amongst both tools and the assumptions incorporated into the BurnSim software. Although there are slight deltas amongst the tools, the BurnSim tool can be utilized to validate the analytical approach for this effort.
Figure xx: Thrust vs. Time Comparison